

VISIT...

LANZAROTE
Caliente.COM

27

Electric Power Utilization: Motors

27.1	Some General Perspectives	27-1
27.2	Operating Modes.....	27-3
27.3	Motor, Enclosure, and Controller Types.....	27-3
27.4	System Design.....	27-3
	Load Requirements • Environmental Requirements •	
	Electrical Source Options • Preliminary System Design •	
	System Ratings • System Data Acquisition •	
	Engineering Studies • Final System Design • Field Testing	

Charles A. Gross

Auburn University

A major application of electric energy is in its conversion to mechanical energy. Electromagnetic, or “EM” devices designed for this purpose are commonly called “motors.” Actually the machine is the central component of an integrated system consisting of the source, controller, motor, and load. For specialized applications, the system may be, and frequently is, designed as a integrated whole. Many household appliances (e.g., a vacuum cleaner) have in one unit, the controller, the motor, and the load. However, there remain a large number of important stand-alone applications that require the selection of a proper motor and associated control, for a particular load. It is this general issue that is the subject of this chapter.

The reader is cautioned that there is no “magic bullet” to deal with all motor-load applications. Like many engineering problems, there is an artistic, as well as a scientific dimension to its solution. Likewise, each individual application has its own peculiar characteristics, and requires significant experience to manage. Nevertheless, a systematic formulation of the issues can be useful to a beginner in this area of design, and even for experienced engineers faced with a new or unusual application.

27.1 Some General Perspectives

Consider the general situation in [Fig. 27.1a](#). The flow of energy through the system is from left to right, or from electrical source to mechanical load. Also, note the positive definitions of currents, voltages, speed, and torques. These definitions are collectively called the “motor convention,” and are logically used when motor applications are under study. Likewise, when generator applications are considered, the sign conventions of [Fig. 27.1b](#) (called generation convention) will be adopted. This means that variables will be positive under “normal” conditions (motors operating in the motor mode, generators in the generator mode), and negative under some abnormal conditions (motors running “backwards,” for example). Using motor convention:

$$T_{dev} - (T_m + T_{RL}) = T_{dev} - T'_m = J(d\omega_{rm}/dt) \quad (27.1)$$

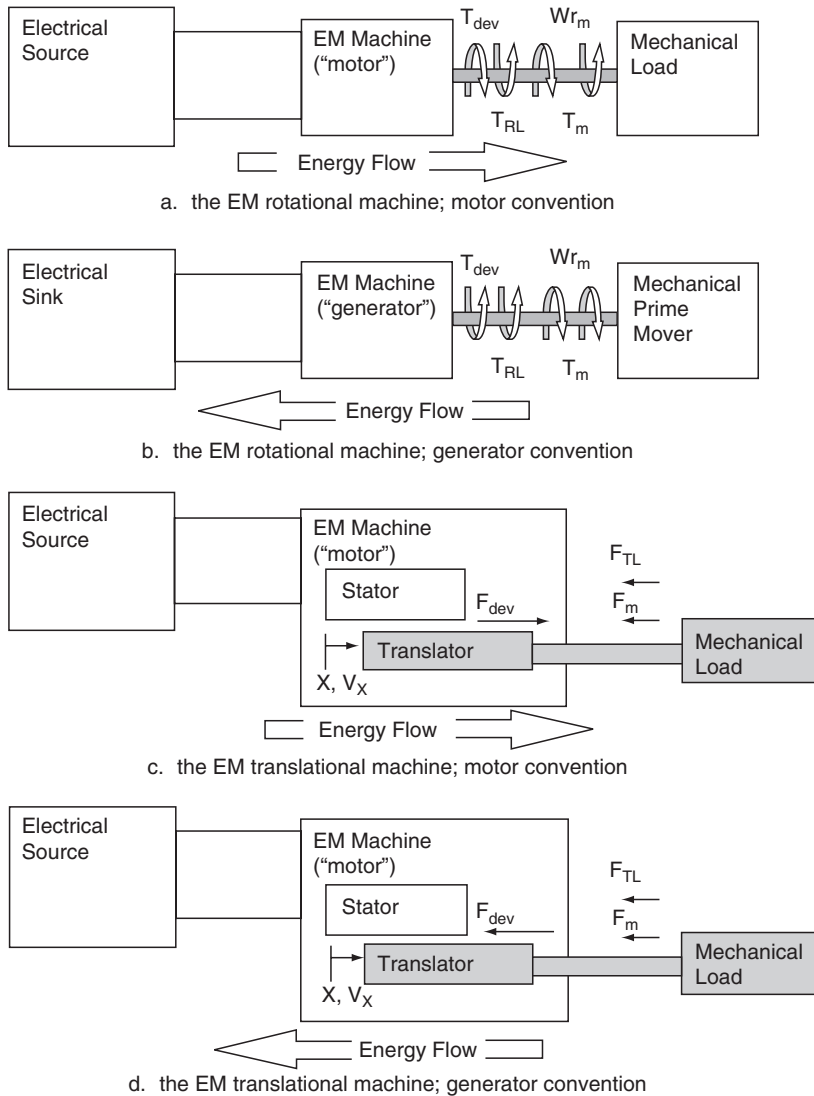


FIGURE 27.1 Motor and generator sign conventions for EM machines.

where T_{dev} = EM torque, produced by the motor, Nm

T_m = torque absorbed by the mechanical load, including the load losses and that used for useful mechanical work, Nm

T_{RL} = rotational loss torque, internal to the motor, Nm

$T'_m = T_m + T_{RL}$ = equivalent load torque, Nm

J = mass polar moment of inertia of all rotating parts, kg-m²

ω_{rm} = angular velocity of rotating parts, rad/s

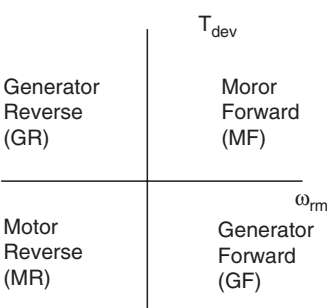
Observe that whenever $T_{dev} > T'_m$, the system accelerates; if $T_{dev} < T'_m$, the system decelerates. The system will inherently seek out the equilibrium condition of $T_{dev} = T'_m$, which will determine the running speed. In general, the steady state running speed for any motor-load system occurs at the intersection of the motor and load torque-speed characteristics, i.e., where $T_{dev} = T'_m$. If $T_{dev} > T'_m$, the system is accelerating; for $T_{dev} < T'_m$, the system decelerates. Thus, torque-speed characteristics for motors and loads are necessary for the design of a speed (or position) control system.

The corresponding system powers are:

$P_{dev} = T_{dev} \omega_{rm}$ = EM power, converted by the motor into mechanical form, W

$P_m = T_m \omega_{rm}$ = power absorbed by the mechanical load, including the load losses and that used for useful mechanical work, W

$P_{RL} = T_{RL} \omega_{rm}$ = rotational power loss, internal to the motor, W



27.2 Operating Modes

FIGURE 27.2 Operating modes.

Equation (27.1) implies that torque and speed are positive. Consider positive speed as “forward,” meaning rotation in the “normal” direction, which should be obvious in a specific application. “Reverse” is defined to mean rotation in the direction opposite to “forward,” and corresponds to $\omega_{rm} < 0$. Positive EM torque is in the positive speed direction. Using motor convention, first quadrant operation means that (1) speed is positive (“forward”) and (2) T_{dev} is positive (also forward), and transferring energy from motor to load (“motoring”). There are four possible operating modes specific to the four quadrants of Fig. 27.2. In any application, a primary consideration is to determine which of these operating modes will be required.

27.3 Motor, Enclosure, and Controller Types

The general types of enclosures, motors, and controllers are summarized in Tables 27.1, 27.2, and 27.3.

27.4 System Design

The design of a proper motor-enclosure-controller system for a particular application is a significant engineering problem requiring engineering expertise and experience. The following issues must be faced and resolved.

TABLE 27.1 General Enclosure Types^a

Types
Open
Drip-proof
Splash-proof
Semi-guarded
Weather protected
Type I
Type II
Totally enclosed
Nonventillated
Fan-cooled
Explosion-proof
Dust-ignition-proof
Water-proof
Pipe-ventilated
Water-cooled
Water-air-cooled
Air-to-air-cooled
Air-over-cooled

^aSee NEMA Standard MG 1.1.25-1.1.27 for definitions.

TABLE 27.2 General Motor Types^a

Type
DC motors (commutator devices)
Permanent magnet field
Wound field
Series
Shunt
Compound
AC motors
Single-phase
Cage rotor
Split phase
Resistance-start
Capacitor start
Single capacitor (start-run)
Capacitor start/capacitor run
Shaded pole
Wound rotor
Repulsion
Repulsion start/induction run
Universal
Synchronous
Hysteresis
Three-phase
Synchronous
Permanent magnet field
Wound field
Induction
Cage rotor
NEMA Design A,B,C,D,F
Wound rotor

^aSee NEMA Standard MG 1.1.1-1.1.21 for definitions.

27.4.1 Load Requirements

1. The steady-state duty cycle with torque-speed (position) requirements at each load step.
2. What operating modes are required.
3. Dynamic performance requirements, including starting and stopping, and maximum and minimum accelerations.
4. The relevant torque-speed (position) characteristics.
5. All load inertias (J).
6. Coupling options (direct drive, belt-drive, gearing).
7. Reliability of service. How critical is a system failure?
8. Future modifications.

27.4.2 Environmental Requirements

1. Ambient atmospheric conditions (pressure, temperature, humidity, content)
2. Indoor, outdoor application
3. Wet, dry location
4. Ventilation
5. Acceptable acoustical noise levels
6. Electrical/mechanical hazards to personnel
7. Accessibility for inspection and maintenance

TABLE 27.3 General Motor Controllers

Type
DC motor controllers
Electromechanical
Armature starting resistance; rheostat field control
Power electronic drive
Phase converters: 1, 2, 4 quadrant drives
Chopper control: 1, 2, 4 quadrant drives
AC motor controllers
Single-phase
Electromechanical
Across-the-line: protection only
Step-reduced voltage
Power electronic drive
Armature control: 1, 2, 4 quadrant drives
Three-phase induction
Cage rotor
Electromechanical
Across-the-line: protection only
Step-reduced voltage
Power electronic drive (ASDs)
Variable voltage source inverter
Variable current source inverter
Chopper voltage source inverter
PWM voltage source inverter
Vector control
Wound rotor
Variable rotor resistance
Power electronic rotor power recovery
Three-phase synchronous
Same as cage rotor induction
Brushless DC control

27.4.3 Electrical Source Options

- 1. DC-AC
- 2. If AC, single- and/or three-phase
- 3. Voltage level
- 4. Frequency
- 5. Capacity (kVA)
- 6. Protection options
- 7. Power quality specifications

27.4.4 Preliminary System Design

Based on the information compiled in the steps above, select an appropriate enclosure, motor type, and controller. In general, the enclosure entries, reading from top to bottom in [Table 27.1](#), are from simplest (and cheapest) to most complex (and expensive). Select the simplest enclosure that meets all the environmental constraints. Next, select a motor and controller combination from [Tables 27.2](#) and [27.3](#). This requires personal experience and/or consulting with engineers with experience relevant to the application.

In general, DC motors are expensive and require more maintenance, but have excellent speed and position control options. Single-phase AC motors are limited to about 5 kW, but may be desirable in locations where three-phase service is not available and control specifications are not critical.

Three-phase AC synchronous motors are not amenable to frequent starting and stopping, but are ideal for medium and high power applications which run at essentially fixed speeds. Three-phase AC

cage rotor induction motors are versatile and economical, and will be the preferred choice for most applications, particularly in the medium power range. Three-phase AC wound rotor induction motors are expensive, and only appropriate for some unusual applications.

The controller must be compatible with the motor selected; the best choice is the most economical that meets all load specifications. If the engineer's experience with the application under study is lacking, two or more systems should be selected.

27.4.5 System Ratings

Based on the steps above, select appropriate power, voltage, and frequency ratings. For cyclic loads, the power rating may tentatively be selected based on the "rms horsepower" method (calculating the rms power requirements over the load cycle).

27.4.6 System Data Acquisition

Request data from at least two vendors on all systems selected in the steps above, including:

- circuit diagrams
- performance test data
- equivalent circuit values, including inertia constants
- cost data
- warranties and guarantees

27.4.7 Engineering Studies

Perform the following studies using data from the system data acquisition step above.

1. Steady state performance. Verify that each candidate system meets all steady state load requirements.
2. Dynamic performance. Verify that each system meets all dynamic load requirements.
3. Load cycle efficiency. Determine the energy efficiency over the load cycle.
4. Provide a cost estimate for each system, including capital investment, maintenance, and annual operating costs.
5. Perform a power quality assessment.

Based on these studies, select a final system design.

27.4.8 Final System Design

Request a competitive bid on the final design from appropriate vendors. Select a vendor based on cost, expectation of continuing technical support, reputation, warranties, and past customer experience.

27.4.9 Field Testing

Whenever practical, customer and vendor engineers should design and perform field tests on the installed system, demonstrating that it meets or exceeds all specifications. If multiple units are involved, one proto-unit should be installed, tested, and commissioned before delivery is made on the balance of the order.

Further Information

The design of a properly engineered motor-controller system for a particular application requires access to several technical resources, including standards, the technical literature, manufacturers' publications, textbooks, and handbooks. The following section provides a list of references and resource material that

the author recommends for work in this area. In many cases, more recent versions of publications listed are available and should be used.

Organizations

American National Standards Institute (ANSI), 1430 Broadway, New York, NY 10018.
Institute of Electrical and Electronics Engineers (IEEE), 445 Hoes Lane, Piscataway, NJ 08855.
International Organization for Standardization (ISO) 1, rue de Varembe, 1211 Geneva 20, Switzerland.
American Society for Testing and Materials (ASTM), 1916 Race Street, Philadelphia, PA 19103.
National Electrical Manufacturers Association (NEMA), 2101 L Street, NW, Washington, D.C. 20037.
National Fire Protection Association (NFPA), Batterymarch Park Quincy, MA 02269.
The Rubber Manufacturers Association, Inc., 1400 K Street, NW, Suite 300, Washington, D.C. 20005.
Mechanical Power Transmission Association, 1717 Howard Street, Evanston, IL 60201.

Standards

NEMA MG 1-1987, *Motors and Generators*.

NEMA MG 2-1983, *Safety Standard for Construction and Guide for Selection, Installation and Use of Electric Motors and Generators*.

NEMA MG 3-1984, *Sound Level Prediction for Installed Rotating Electrical Machines*.

NEMA MG 13-1984, *Frame Assignments for Alternating-Current Integral-horsepower Induction Motors*.

ANSI/NFPA 70-1998, *National Electrical Code*.

IEEE Std 1-1969, *General Principles for Temperature Limits in the Rating of Electric Equipment*.

IEEE Std 85-1980, *Test Procedure for Airborne Sound Measurements on Rotating Electric Machinery*.

ANSI/IEEE Std 100-1984, *IEEE Standard Dictionary of Electrical and Electronics Terms*.

IEEE Std 112-1984, *Standard Test Procedure for Potyphase Induction Motors and Generators*.

IEEE Std 113-1985, *Guide on Test Procedures for DC Machines*.

ANSI/IEEE Std 114-1984, *Test Procedure for Single-Phase Induction Motors*.

ANSI/IEEE Std 115-1983, *Test Procedures for Synchronous Machines*.

ANSI/IEEE Std 117-1985, *Standard Test Procedure for Evaluation of Systems of Insulating Materials for Random-Wound AC Electric Machinery*.

ANSI/IEEE Std 304-1982, *Test Procedure for Evaluation and Classification of Insulation Systems for DC Machines*.

ISO R-1000, *SI Units and Recommendations for the Use of their Multiples and of Certain Other Units*.

Books (an abridged sample)

Aearnley, P.P., *Stepping Motors*, 2nd ed., Peter Peregrinus, Ltd., London, 1984.

Anderson, L.R., *Electric Machines and Transformers*, Reston Publishing, Reston, VA, 1981.

Bergseth, F.R. and Venkata, S.S., *Introduction to Electric Energy Devices*, Prentice-Hall, Englewood Cliffs, NJ, 1987.

Bose, B.K., *Power Electronics and AC Drives*, Prentice-Hall, Englewood Cliffs, NJ, 1985.

Brown, D. and Hamilton 111, E.P., *Electromechanical Energy Conversion*, Macmillan, New York, 1984.

Chapman, S.J., *Electric Machinery Fundamentals*, McGraw-Hill, New York, 1985.

DC Motors-Speed Controls-Servo Systems—An Engineering Handbook, 5th ed., Electro-Craft Corporation, Hopkins, MN, 1980.

Del Toro, V., *Electric Machinery and Power Systems*, Prentice-Hall, Englewood Cliffs, NJ, 1986.

Electro-Craft Corporation, *DC Motors, Speed Controls, Servo Systems*, 3rd ed., Pergamon Press, Ltd., Oxford, 1977.

Fitzgerald, A.E., Kingsley, Jr., C., and Umans, S.D., *Electric Machinery*, 5th ed., McGraw-Hill, New York, 1990.

Gonen, T., *Engineering Economy for Engineering Managers*, Wiley, New York, 1990.

- Kenjo, T. and S. Nagamori, *Permanent-Magnet and Brush-less DC Motors*, Oxford, Claredon, 1985.
- Krause, P.C. and Waszynek, O., *Electromechanical Machines and Devices*, McGraw-Hill, New York, 1989.
- Krein, P., *Elements of Power Electronics*; Oxford Press, 1998.
- Moha, N., Undeland, and Robbins, *Power Electronics; Converters, Application, and Design, 2nd ed.*, John Wiley & Sons, New York, 1995.
- Nasar, S.A. and Boldea, I., *Linear Motion Electric Machines*, John Wiley & Sons, New York, 1976.
- Nasar, S.A., Ed., *Handbook of Electric Machines*, McGraw-Hill, New York, 1987.
- Patrick, D.R. and Fardo, S.W., *Rotating Electrical Machines and Power Systems*, Prentice-Hall, Englewood Cliffs, NJ, 1985.
- Ramshaw, R. and Van Heeswijk, R.G., *Energy Conversion: Electric Motors and Generators*, Saunders College Publishing, Orlando, FL, 1990.
- Rashid, M.H., *Power Electronics: Circuits, Devices, and Applications, 2nd ed.*, Prentice-Hall, Englewood Cliffs, NJ, 1993.
- Sarma, M.S., *Electric Machines: Steady-State Theory and Dynamic Performance*, Brown Publishers, Dubuque, IA, 1985.
- Smeaton, R.W., Ed., *Motor Application and Maintenance Handbook*, McGraw-Hill, New York, 1969.
- Stein, R., and Hunt, W.T., *Electric Power System Components: Transformers and Rotating Machines*, Van Nostrand, New York, 1979.
- Veinott, C.G. and Martin, J.E., *Fractional- and Subfractional-Horsepower Electric Motors*, 4th ed., McGraw-Hill, New York, 1986.
- Wenick, E.H., ed., *Electric Motor Handbook*, McGraw-Hill, London, 1978.